

425 F-005

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
21 February 2002 (21.02.2002)

PCT

(10) International Publication Number
WO 02/15283 A2

(51) International Patent Classification: H01L 31/0328

(21) International Application Number: PCT/US01/25161

(22) International Filing Date: 10 August 2001 (10.08.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/638,384 12 August 2000 (12.08.2000) US

(71) Applicant and

(72) Inventor: BRADDOCK, Walter, David, IV [US/US];
300 First St. N.E., Rochester, MN 55906 (US).

(74) Agent: BRADDOCK, Christopher, T.; 217 East Seventh
Avenue, Denver, CO 80203 (US).

CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,
GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC,
LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW,
MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK,
SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, ZA,
ZW.

(84) Designated States (regional): ARIPO patent (GH, GM,
KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian
patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European
patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE,
IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF,
CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD,
TG).

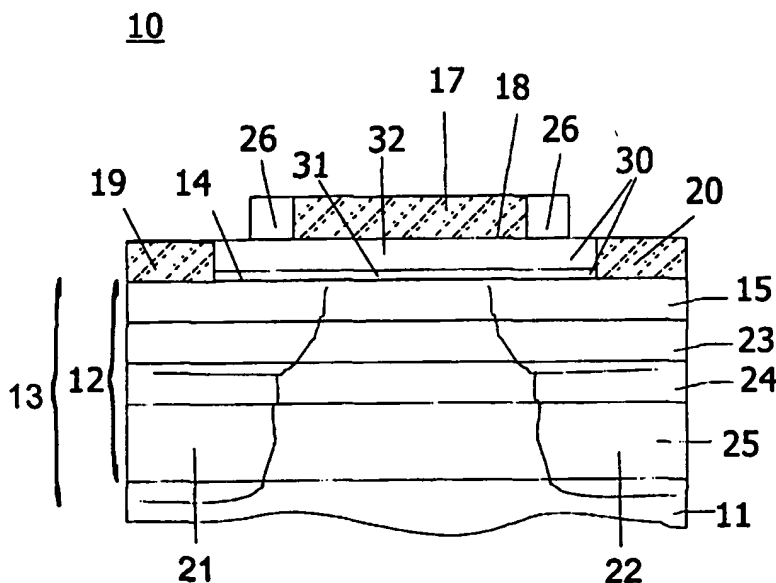
Published:

— without international search report and to be republished
upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guid-
ance Notes on Codes and Abbreviations" appearing at the begin-
ning of each regular issue of the PCT Gazette.

(81) Designated States (national): AE, AG, AL, AM, AT, AU,
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,

(54) Title: METAL SULFIDE-OXIDE SEMICONDUCTOR TRANSISTOR DEVICES



(57) Abstract: A self-aligned enhancement mode metal-sul-
fide-oxide-compound semiconductor field effect transistor (10) includes a lower sulfide layer that is a mixture of Ga_2S , Ga_2S_3 , and other gallium sulfide compounds (30), and a second insulating layer that is positioned immediately on top of the gallium sulphur layer together positioned on upper surface (14) of a III-V compound semiconductor wafer structure (13). Together the lower gallium sulfide compound layer and the second insulating layer form a gallium sulfide-oxide gate insulating structure. The gallium sulfide-oxide gate insulating structure and underlying compound semiconductor gallium arsenide layer (15) meet at an atomically abrupt interface at the surface of

with the compound semiconductor wafer structure (14). The initial essentially gallium sulphur layer serves to passivate and protect the underlying compound semiconductor surface from the second insulating sulfide layer. The insulating layer deposited upon the gallium sulphur layer is composed of gallium oxygen and at least one rare earth elemental layer deposited so that it is highly insulating in nature. A refractory metal gate electrode layer (17) is positioned on upper surface (18) of the second insulating sulfide layer. The refractory metal is stable on the second insulating oxide layer at elevated temperature. Self-aligned source and drain areas, and source and drain contacts (19, 20) are positioned on the source and drain areas (21, 22) of the device. Multiple devices are then positioned in proximity and the appropriate interconnection metal layers and insulators are utilized in concert with other passive circuit elements to form an integrated circuit structure.

WO 02/15283 A2

Metal Sulfide-Oxide Semiconductor Transistor Devices

5

FIELD OF THE INVENTION

The present invention pertains to low power and high speed integrated circuits in the compound semiconductor field utilizing field effect transistors and more specifically complementary field effect transistors used in concert including enhancement mode self-aligned metal-insulator-compound semiconductor transistors and depletion mode self-aligned metal-sulfide-compound semiconductor transistors and methods of materials growth and fabrication of said structures and the ultra large scale integration of said transistors.

BACKGROUND OF THE INVENTION

The gallium arsenide and indium phosphide integrated circuit industry has been limited without a technology that simultaneously allows the integration of complementary field effect transistor devices and transistors with low gate leakage currents. In contrast to silicon technology that has a very mature and useful complementary metal oxide semiconductor (CMOS) technology. Field effect transistor (FETs) widely used in the III-V semiconductor industry employ metal gates and Schottky gate contacts that have quiescent-state leakage currents exceeding many microamps. The use of metal gates in compound semiconductor technology further results in individual transistors and integrated circuits that have excessively high power dissipation, reduced transconductance, reduced logic swing and the inability to operate on a single power supply, and generally limited performance characteristics. The high magnitude of the quiescent leakage current limits the maximum integration of GaAs devices to circuits of several hundred thousand transistors for those skilled in the art. In contrast, the simultaneous integration of many millions of transistors is possible at high integration densities using silicon CMOS technology. These ultra high

integration densities and levels cannot be obtained using metal, Schottky-style gates that are not insulated in compound semiconductor FETs. Thus Si CMOS technology offers significant advantages in terms of individual gate leakage, circuit integration level and cost. However when compared to silicon, complementary GaAs and InP circuit technology

5 exhibits faster and more optimized speed/power performance and efficiency at a low supply voltage of 1V and below. The market acceptance of these GaAs and InP integrated circuit technologies remains low because of the lack of ability to demonstrate high integration densities with low amounts of operating power. Thus, silicon CMOS dominates the field of digital integrated circuitry and neither GaAs nor InP technologies can successfully penetrate

10 this market.

What is needed are new and improved compound semiconductor field effect transistors (FET). What is also needed are new and improved compound semiconductor FETs using metal-insulator-semiconductor junctions (MISFET). What is also needed are new and improved compound semiconductor MISFETs using a self-aligned gate structure. What is

15 also needed are new and improved self-aligned compound semiconductor MISFETs using enhancement mode and depletion mode operation. What is also needed are new and improved self-aligned compound semiconductor MISFETs with stable and reliable device operation. What is also needed are new and improved self-aligned compound semiconductor MISFETs which enable optimum compound semiconductor device performance. What is also needed

20 are new and improved self-aligned compound semiconductor MISFETs with optimum efficiency and output power for RF and microwave applications. What is also needed are new and improved self-aligned compound semiconductor MISFETs for use in complementary circuits and architectures. What is also needed are new and improved self-aligned compound semiconductor MISFETs for low power/high performance complementary circuits and

25 architectures. What is also needed are new and improved self-aligned compound

semiconductor MISFETs which offer the design flexibility of complementary architectures. What is also needed are new and improved self-aligned compound semiconductor MISFETs which keep interconnection delays in ultra large scale integration under control. What is needed are new and useful complementary integrated circuits where each individual transistor

5 has a leakage current approaching 10^{-12} amp. What is needed is a truly useful integrated circuit technology for GaAs and InP that allows for the useful and economical operation of ULSI digital integrated circuits in compound semiconductors. What is needed are new and improved compound semiconductor MISFET integrated circuits with very low net power dissipation. What is needed are new and improved compound semiconductor MISFET

10 devices with low gate leakage currents that may be integrated together to form ultra large scale integrated circuits that include millions of transistors. What is needed are new and improved complementary MISFET devices and circuits in compound semiconductors that allow the direct use, transfer and application of silicon CMOS design that already exists in the art.

15 What is also needed are new and improved methods of fabrication of self-aligned compound semiconductor MISFETs. What is also needed is new and improved methods of fabrication of self-aligned compound semiconductor MISFETs which are compatible with established complementary GaAs heterostructure FETs technologies. What is also needed are new and improved compound semiconductor MISFETs which are relatively easy to fabricate and use.

20 **BRIEF DESCRIPTION OF THE DRAWINGS**

A more complete understanding of the present invention may be derived by referring to the detailed description and claims when considered in connection with the figures, wherein like reference numbers refer to similar items throughout the figures, and:

FIG. 1 is simplified cross sectional view of a self-aligned enhancement mode compound

25 semiconductor MISFET in accordance with a preferred embodiment of the present invention;

FIG. 2 is a simplified flow chart illustrating a method of manufacturing a self-aligned enhancement mode compound semiconductor MISFET in accordance with a preferred embodiment of the present invention.

The exemplification set out herein illustrates a preferred embodiment of the invention in one form thereof, and such exemplification is not intended to be construed as limiting in any manner.

DETAILED DESCRIPTION OF THE DRAWINGS

The present invention provides, among other things, a self-aligned enhancement mode metal-insulator-compound semiconductor FET. The FET includes a gallium sulphur oxygen rare earth insulating structure that is composed of at least two distinct layers. The first layer is most preferably more than 10 angstroms thick but less than 25 angstroms in thickness and composed substantially of gallium sulphur compounds including but not limited to stoichiometric Ga_2S_3 , GaS , and Ga_2S , and possibly a lesser fraction of other gallium sulphur compounds. The upper insulating layer in the insulating structure is composed of an insulator that does not intermix with the underlying gallium sulphide insulating structure. This upper layer must possess excellent insulating qualities, and is most typically composed of gallium oxygen and a third rare earth element that together form a ternary insulating material. Therefore the entire gallium sulfide-oxide rare earth gate insulator structure is composed of at least two layers and may contain a third intermediate graded layer that consists of a mixture of the upper insulating material and the gallium sulphur compounds that compose the initial layer. Together the initial gallium sulphur layer, any intermediate graded layer and the top insulating region form both a gallium sulfide insulating structure and the gate insulator region of a metal-sulfide-compound semiconductor field effect transistor. The initial substantially gallium sulphur layer forms an atomically abrupt interface with the top layer of the compound semiconductor wafer structure, and does not introduce midgap surface states into

the compound semiconductor material. A refractory metal gate electrode is preferably positioned on the upper surface of the gate insulator structure layer. The refractory metal is stable on the gate insulator structure layer at elevated temperature. Self-aligned source and drain areas, and source and drain contacts are positioned on the source and drain areas. In all

5 embodiments preferred and otherwise, the metal-sulfide-compound semiconductor transistor includes multi-layer gate insulator structure including an initial gallium sulphur layer, intermediate transition layer, and upper insulating layer of 30-250 angstroms in thickness positioned on upper surface of a compound semiconductor heterostructure that form the gate insulator structure. The preferred embodiment also comprises a compound semiconductor

10 heterostructure including a GaAs, $Al_x Ga_{1-x}As$ and $In_y Ga_{1-y}As$ layers with or without n-type and/or p-type charge supplying layers which are grown on a compound semiconductor substrate, a refractory metal gate of W, WN, or WSi, self aligned donor (n-channel FET) or acceptor (p-channel FET) implants, and source and drain ohmic contacts. In another preferred embodiment, the compound semiconductor heterostructure comprises an $In_y Ga_{1-y}As$, $Al_x In_{1-x}As$, and InP compound semiconductor heterostructure and n-type and/or p-type

15 charge supplying layers which are grown on an InP substrate, and a refractory metal gate of W, WN, or WSi, self aligned donor (n-channel FET) or acceptor (p-channel FET) implants, and source and drain ohmic contacts.

FIG. 1 is simplified cross sectional view of a self-aligned enhancement mode compound

20 semiconductor MISFET in accordance with a preferred embodiment of the present invention. Device 10 includes a compound semiconductor material, such as any III-V material employed in any semiconductor device, represented herein by a III-V semiconductor substrate 11 and a compound semiconductor epitaxial layer structure 12. For the purpose of this disclosure, the substrate 11 and any epitaxial layer structure 12 formed thereon will be

25 referred to simply as a compound semiconductor wafer structure which in FIG. 1 is

designated 13. Methods of fabricating semiconductor wafer structure 13 include, but are not limited to, molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD). It will of course be understood that in some specific applications, there may be no epitaxial layers present and upper surface of top layer 15 may simply be the upper surface of substrate 11.

Device 10 further comprises a gate insulator structures (30) that includes at least two or more layers. The first layer of the gate insulator structure (31) is composed entirely of gallium sulfide compounds and is directly adjacent to and deposited upon the compound semiconductor structure. The second layer of the gate insulator structure (32) is composed of a compound of gallium, oxygen, and one or more rare earth elements from the periodic table. The initial gallium sulphur layer (31) forms an atomically abrupt interface 14 with the upper surface of top layer 15, the top layer of the compound semiconductor structure. A refractory metal gate electrode 17 which is stable in the presence of top gallium oxygen rare earth insulating material at elevated temperature is positioned on upper surface 18 of the gate insulator structure. Dielectric spacers 26 are positioned to cover the sidewalls of metal gate electrode 17. Source and drain contacts 19 and 20 are deposited on self-aligned source and drain areas 21 and 22, respectively.

In a specific embodiment, the compound semiconductor epitaxial layer structure consists of a <11 angstrom GaAs top layer (15), a <101 angstrom $\text{Al}_x\text{Ga}_{1-x}\text{As}$ spacer layer (23), a <251 angstrom $\text{In}_y\text{Ga}_{1-y}\text{As}$ channel layer (24), and a GaAs buffer layer (25) grown on a GaAs substrate (11). Top GaAs layer (15) is used to form an atomically abrupt layer with the gate insulator structure with an abrupt interface with low defect density.

As a simplified example of fabricating a self-aligned enhancement mode compound semiconductor MISFET in accordance with a preferred embodiment of the present invention, a III-V compound semiconductor wafer structure 13 with an atomically ordered and

chemically clean upper surface of top layer 15 is prepared in an ultra-high vacuum semiconductor growth chamber and transferred via a ultra high vacuum transfer chamber to a second ultra high vacuum sulfide and insulator deposition chamber. The initial gallium sulphur layer (31) is deposited on upper compound semiconductor surface layer 15 using thermal evaporation from a high purity Ga_2S_3 source or from crystalline gadolinium gallium sulphide, $Ga_3Gd_5S_{12}$. This initial gallium sulphur layer is deposited while holding the substrate temperature of the compound semiconductor structure at $<500^{\circ}C$, and most preferably at a substrate temperature $<395^{\circ}C$. After the deposition of approximately 18 angstroms of gallium sulphur compounds in the insulator deposition chamber over a 5 to 8 minute period of time, the compound semiconductor structure is transferred to an oxide deposition chamber where deposition of the second insulator layer is initiated. The deposition of the second insulator layer starts by directing the flux from a low power oxygen plasma source into the ultra high vacuum system such that the oxygen plasma effluent and species are largely directed toward and impinging upon said compound semiconductor structure with initial gallium sulphide layer. The flux from the oxygen plasma source should be directed at the surface for between 2-5 seconds, subsequently followed by the co-evaporation of gallium oxide compounds from Ga_2O_3 and a second thermal evaporation source that contains a rare-earth element. The flux beams from the oxygen plasma source, Ga_2O_3 and rare-earth evaporation source thermal evaporation sources are carefully balanced to provide a ternary insulator layer on top of the initial gallium sulphide layer on said compound semiconductor structure. As the deposition of the second ternary oxide insulator layer is initiated, the substrate temperature is simultaneously adjusted to provide an optimized substrate temperature for the deposition of this layer. In this example the substrate temperature required to deposit the gallium+oxygen+rare earth layer is $<530^{\circ}C$. The deposition of this second insulator layer proceeds until the total insulator thickness of 200-250 angstroms is

achieved. Shutters and valves are utilized to stop the deposition of the ternary gallium+sulphur+rare earth layer upon the deposition of the required thickness of the insulator layer. The substrate temperature is cooled in-vacuum to $<200^{\circ}\text{C}$, and the deposition of a refractory metal which is stable and does not interdiffuse with on the top layer of the gate insulator structure at elevated temperature such as WSi or WN is deposited on upper surface 18 of sulfide layer 32 and subsequently patterned using standard lithography. The refractory metal layer is etched until sulfide layer 31 is exposed using a refractory metal etching technique such as a fluorine based dry etching process. The refractory metal etching procedure does not etch the sulfide layer 31, thus, sulfide layer 31 functions as an etch stop layer such that upper surface of top layer 15 remains protected by sulfide layer 31. All processing steps are performed using low damage plasma processing. Self-aligned source and drain areas 21 and 22, respectively are realized by ion implantation of Si (n-channel device) and Be/F or C/F (p-channel device) using the refractory metal gate electrode 17 and the dielectric spacers 26 as implantation masks. Such ion implantation schemes are compatible with standard processing of complementary compound semiconductor heterostructure FET technologies and are well known to those skilled in the art. The implants are activated at $700-900^{\circ}\text{C}$ using rapid thermal annealing in an ultra high vacuum environment such that degradation of the interface 16 established between top layer 15 and sulfide layer 31 is completely excluded. Finally, ohmic source and drain contacts 19 and 20 are deposited on the self-aligned source and drain areas 21 and 22, respectively. The devices may then be interconnected using the standard methods to those skilled in the art of integrated microelectronics and integrated circuit manufacture.

FIG. 2 is a simplified flow chart illustrating a method of manufacturing a self-aligned enhancement mode compound semiconductor MISFET in accordance with a preferred embodiment of the present invention. In step 102, a compound semiconductor wafer structure

is produced using standard epitaxial growth methods in the art. In step 103, a layer consisting of gallium sulphide compounds including but not limited to Ga_2S_3 , Ga_2S , GaS is deposited on upper surface of said compound semiconductor wafer structure. The wafer is then transferred to an oxide deposition chamber. In step 104, an insulating layer of gallium oxide and one or more rare earth elements is deposited on the upper surface of the initial gallium oxide compound layer. The gallium oxide gate insulator structure is formed in steps 104 and 105. In step 106, a stable refractory gate metal is positioned on upper surface of said gate insulator structure. In step 108, source and drain ion implants are provided self-aligned to the gate electrode. In step 110, source and drain ohmic contacts are positioned on ion implanted source and drain areas.

In a preferred embodiment, step 100 provides a compound semiconductor substrate such as GaAs or InP. Step 102 includes the preparation and epitaxial growth of an atomically ordered and chemically clean upper surface of the compound semiconductor wafer structure. Step 103 preferably comprises thermal evaporation from a purified and crystalline gadolinium gallium sulphide or Ga_2S_3 source on an atomically ordered and chemically clean upper surface of the compound semiconductor wafer structure. Step 104 comprises the formation of a gallium+oxide+rare earth elemental insulating layer formed through the simultaneous vacuum evaporation of gallium sulphur species and at least one rare earth element such as Gadolinium with the simultaneous sulphidization using the effluent of an sulphur gas plasma source directed in simultaneous combination with other thermal evaporation sources toward substrate 100. The initial gallium sulphur compound layer of the gate insulator structure preferably functions as an etch stop layer such that the upper surface of the compound semiconductor wafer structure remains protected by the gate gallium sulfide layer during and after gate metal etching. The refractory gate metal desirably does not react with or diffuse into the gallium oxide rare earth layer during high temperature annealing of the self-aligned

source and drain ion implants. The quality of the interface formed by the gate sulfide layer and the upper surface of the compound semiconductor structure is desirably preserved during high temperature annealing of the self-aligned source and drain ion implants. The self-aligned source and drain implants are desirably annealed at approximately 700°C in an ultra high vacuum environment. The self-aligned source and drain implants are desirably realized by positioning dielectric spacers on the sidewalls of the refractory gate metal.

Thus, new and improved compound semiconductor devices and methods of fabrication are disclosed. The new and improved self-aligned enhancement mode metal-sulfide-compound semiconductor heterostructure field effect transistors enable stable and reliable device operation, provide optimum compound semiconductor device performance for low power/high performance complementary circuits and architectures, keep interconnection delay in ULSI under control, and provide optimum efficiency and output power for RF and microwave applications as well as for digital integrated circuits that require very high integration densities.

These improvements essentially solve or overcome the problems of the prior art, such as high gate leakage in compound semiconductor FET devices, low integration densities, dc electrical instability, and electrical hysteresis, and therefore provide a highly useful invention. While we have shown and described specific embodiments of the present invention, further modifications and improvements will occur to those skilled in the art. We desire it to be understood, therefore, that this invention is not limited to the particular forms shown and we intend in the appended claims to cover all modifications that do not depart from the spirit and scope of this invention.

What is claimed:

1. An enhancement mode metal-sulfide-compound semiconductor field effect transistor comprising:

5 a compound semiconductor wafer structure having an upper surface;

10 a layer composed of the compounds of gallium and sulphur including but not limited to mixtures of Ga_2S_3 , Ga_2S , GaS and other gallium sulphur compounds positioned on upper surface of said compound semiconductor wafer structure;

15 a second insulating layer composed of the compounds of gallium and oxygen and at least one or more rare earth elements that form an insulating layer deposited on top of the initial supporting gallium sulphur layer, with said first and second layers forming a gate insulator structure adjacent to and on top of the compound semiconductor structure;

a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure layers;

20 source and drain ion implants self-aligned to the gate electrode; and

source and drain ohmic contacts positioned on ion implanted source and drain areas;

25 wherein the refractory metal gate electrode comprises a refractory metal selected from the group consisting of W, WN or WSi or combinations thereof;

means of interconnection of said transistors forming a monolithically integrated circuit.

30 2. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the initial layer of gallium sulphur compounds forms an atomically abrupt interface with the upper surface of the compound semiconductor wafer structure.

35 3. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the gate insulator structure is composed of three layers, an initial gallium sulphur compound layer, a graded layer that contains varying compositions of gallium, sulphur, oxygen and at least one rare-earth element, and a third insulator layer that is composed largely of a compound of gallium, oxygen and one or more rare earth elements.

40 4. An enhancement mode metal-sulfide-compound semiconductor field effect transistor as claimed in claim 1 wherein the gate insulator structure is composed of more than three multiple layers, an initial gallium sulphur compound layer, and multiple layers containing gallium and sulphur and oxygen with or without the inclusion of one or more rare earth elements that together form an insulating gallium sulfide gate insulator structure.

45 5. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the initial gallium sulphur compound layer has a thickness of more than 10 angstroms and less than 25 angstroms.

6. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the gate insulator structure has an overall total thickness of 20-300 angstroms.
- 5 7. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the initial gallium sulphur compound layer forms an atomically abrupt interface with the compound semiconductor structure that extend less than four atomic layers in depth of structural interface modulation.
- 10 8. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the initial gallium and sulphur compound layer and the gate insulator structure protects the upper surface of the compound semiconductor wafer structure.
- 15 9. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the refractory metal gate electrode comprises a refractory metal which is stable in presence of the top layer of the gate insulator structure at an elevated temperature of 700°C and above.
- 20 10. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the source and drain ion implants comprising said enhancement mode metal-sulfide-compound semiconductor field effect transistor being an n-channel device or p-channel device.
- 25 11. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the source and drain ion implants comprise and Be/F or C/F, said enhancement mode metal-sulfide-compound semiconductor field effect transistor being a p-channel device.
- 30 12. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 1 wherein the upper surface of the compound semiconductor wafer structure comprises GaAs.
- 35 13. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 1 wherein the upper surface of the compound semiconductor wafer structure comprises $\text{In}_x\text{Ga}_{1-x}\text{As}$.
14. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor comprising:
- 40 a compound semiconductor wafer structure having an upper surface;
- a layer composed of the compounds of gallium and sulphur compounds including but not limited to mixtures of Ga_2S_3 , Ga_2S and other gallium sulphur compounds positioned on upper surface of said compound semiconductor wafer structure;
- 45 a second insulating layer deposited upon the first composed of the compounds of gallium and oxygen and at least one or more rare earth elements such that the normalized relative composition of gallium, oxygen, sulphur, and one or more rare earth elements are changing in a monotonic manner as a function of the thickness within said insulating layer;

- 5 a third insulating layer deposited on top of said second layer composed of gallium oxygen and at least one or more rare earth elements wherein said first, second and third layers form a gate insulator structure adjacent to and deposited on top of the compound semiconductor structure;
- a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure layers;
- 10 source and drain ion implants self-aligned to the gate electrode; and
- source and drain ohmic contacts positioned on ion implanted source and drain areas;
- wherein the refractory metal gate electrode comprises a refractory metal selected from the group consisting of W, WN or WSi or combinations thereof;
- 15 means of interconnection of said transistors forming a monolithic integrated circuit.
15. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 14 wherein the initial layer of gallium sulphur compounds forms an atomically abrupt interface with the upper surface of the compound semiconductor wafer structure.
- 20 16. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 14 wherein the gate insulator structure is composed of three or more layers, an initial gallium sulphur compound layer, a graded layer that contains varying compositions of gallium sulphur, oxygen and at least one rare-earth element, and a third insulator layer that is composed largely of a compound of gallium, oxygen and one or more rare earth elements.
- 25 17. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 14 wherein the initial gallium sulphur compound layer has a thickness of more than 10 angstroms and less than 25 angstroms.
- 30 18. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 14 wherein the overall gate insulator structure has an overall total thickness of 20-300 angstroms.
- 35 19. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 14 wherein the initial gallium sulphur compound layer forms an atomically abrupt interface with the compound semiconductor structure that extend less than four atomic layers in depth of modulation of said interface.
- 40 20. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 14 wherein the initial gallium and sulphur compound layer and the gate insulator structure protects the upper surface of the compound semiconductor wafer structure.
- 45 21. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect

transistor as claimed in claim 14 wherein the refractory metal gate electrode comprises a refractory metal which is stable in presence of the top layer of the gate insulator structure at an elevated temperature of 700°C and above.

5 22. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 14 wherein the source and drain ion implants comprising said enhancement mode metal-sulfide-compound semiconductor field effect transistor being an n-channel device.

10 23. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 14 wherein the source and drain ion implants comprise and Be/F and C/F, said enhancement mode metal-sulfide-compound semiconductor field effect transistor being a p-channel device.

15 24. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 14 wherein the upper surface of the compound semiconductor wafer structure comprises GaAs.

20 25. An enhancement mode metal-sulfide-oxide-compound semiconductor field effect transistor as claimed in claim 14 wherein the upper surface of the compound semiconductor wafer structure comprises $\text{In}_x\text{Ga}_{1-x}\text{As}$.

25 26. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor comprising:

a compound semiconductor wafer structure having an upper surface;

30 a multilayer gate insulator structure composed of alternating layers comprised of gallium, sulphur, oxygen at least one rare-earth element forming a gate insulator with low electronic midgap defect density positioned on upper surface of said compound semiconductor wafer structure;

a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure layer;

35 source and drain ion implants self-aligned to the gate electrode; and

source and drain ohmic contacts positioned on ion implanted source and drain areas,

40 wherein dielectric spacers are positioned on sidewalls of the stable refractory gate metal electrode.

27. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor comprising:

45 a compound semiconductor wafer structure having an upper surface;

a gate insulator structure positioned on upper surface of said compound semiconductor wafer structure;

a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure;

5 source and drain ion implants self-aligned to the gate electrode; and

source and drain ohmic contacts positioned on ion implanted source and drain areas,

10 wherein the compound semiconductor wafer structure comprises a wider band gap spacer layer and a narrower band gap channel layer.

28. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 27 wherein the wider band gap spacer layer is positioned between the gate sulfide layer and the narrower band gap channel layer.

15

29. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 27 wherein the wider band gap spacer layer has a thickness of between 3-200 angstroms

20

30. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 27 wherein the wider band gap spacer layer comprises either $\text{Al}_x\text{Ga}_{1-x}\text{As}$, InP , or $\text{In}_x\text{Ga}_{1-x}\text{P}$ or a combination thereof.

25

31. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 27 wherein the narrower band gap channel layer has a thickness of 10-300 angstroms.

30

32. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 27 wherein the narrower band gap channel layer is positioned between the wider band gap spacer layer and a buffer layer.

33. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 27 wherein the narrower band gap channel layer comprises $\text{In}_y\text{Ga}_{1-y}\text{As}$.

35

34. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor comprising:

a compound semiconductor wafer structure having an upper surface;

40

a gate insulator structure positioned on upper surface of said compound semiconductor wafer structure;

45 a stable refractory metal gate electrode positioned on upper surface of said gate insulator structure layer;

source and drain ion implants self-aligned to the gate electrode; and

source and drain ohmic contacts positioned on ion implanted source and drain areas,

wherein the compound semiconductor wafer structure comprises a $\text{Al}_x\text{Ga}_{1-x}\text{As}$, $\text{In}_y\text{Ga}_{1-y}\text{As}$, InP , or $\text{In}_z\text{Ga}_{1-z}\text{P}$ layer, said layer being positioned on upper surface of a compound semiconductor substrate.

5

35. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 34 wherein the compound semiconductor substrate includes a GaAs based semiconductor wafer.

10

36. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 34 wherein the compound semiconductor substrate includes a InP based semiconductor wafer.

15

37. An enhancement mode metal-sulfide-oxide compound semiconductor field effect transistor as claimed in claim 1, 13, 26, and 33 that may be integrated together with similar and complementary transistor devices to form complementary metal-sulfide compound semiconductor integrated circuits.

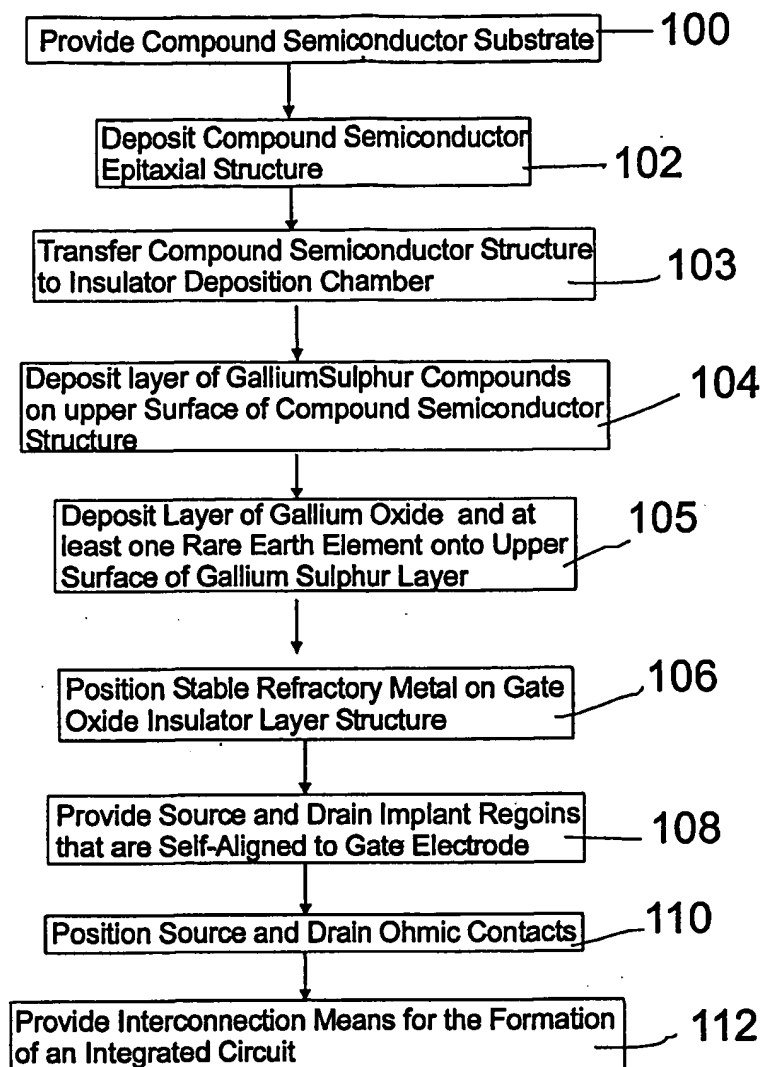


Figure 2